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14. ABSTRACT

As part of the DURIP Equipment Grant from AFOSR with Contract No. F49620-99-1-0216, a technique has been developed to determine the critical interface fracture parameters of dissimilar material interfaces. This technique combines the experimental measurements at the micro-scale and analytical and numerical modeling at the macro-scale. With this grant, our Hitachi scanning electron microscope (SEM, backscatter, and X-ray), Model X-650, has been upgraded with a new 100-lb tensile sub-stage, three-point bending fixture load cell, and an extensometer, heating and cooling accessory (-130°C to 200°C). Also, the SEM has been refurbished with a Kevex-SIGMA fully loaded KS2 Level 2 microanalysis system with Digital Imaging and spectral processing model. With this instrumentation, the SEM provides the capability to characterize material at the micro-level, and permits capturing the effect of micro-properties in macro-analysis when determining engineering properties useful in design. As part of this grant, two graduate students involved in the research project funded by Semiconductor Research Corporation (SRC) have benefited significantly. Also, an undergraduate student received a summer internship from SRC to work on interface characterization with this technique.

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AN INVERSE APPROACH FOR CAPTURING THE INTERACTION OF MACRO- AND MICRO-SCALES IN CHARACTERIZING BONDED COMPOSITE JOINTS

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Summary

As part of the DURIP Equipment Grant from AFOSR with Contract No. F49620-99-1-0216, a technique has been developed to determine the critical interface fracture parameters of dissimilar material interfaces. This technique combines the experimental measurements at the micro-scale and analytical and numerical modeling at the macro-scale.

With this grant, our Hitachi scanning electron microscope (SEM, backscatter, and X-ray), Model X-650, has been upgraded with a new 100-lb tensile sub-stage, three-point bending fixture load cell, and an extensometer, heating and cooling accessory (-130°C to 200°C). Also, the SEM has been refurbished with a Kevex-SIGMA fully loaded KS2 Level 2 microanalysis system with Digital Imaging and spectral processing model.

With this instrumentation, the SEM provides the capability to characterize material at the micro-level, and permits capturing the effect of micro-properties in macro-analysis when determining engineering properties useful in design.

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Background

The strength of the interface between dissimilar materials is a major concern in electronics industry. Under the operational temperature excursions, the extreme mismatch in coefficients of thermal expansion between silicon and underfill and between underfill and organic substrate induces high stresses in the interfaces of electronic components. Fundamental issues associated

with dissimilar material interfaces arise primarily from the lack of information regarding critical interface fracture parameters. Reliable strength predictions of regions involving an interface cannot be made unless the critical values of fracture parameters are available. As pointed out by Mahajan et al. (1999), measurement of the interface strength or critical interface fracture parameters is still an open issue.

The analysis of complex regions can be achieved by employing the finite element method in conjunction with failure prediction criteria such as the energy release rate. However, this parameter is usually calculated from macro parameters such as the applied loads and displacements. Therefore, it does not necessarily reflect the conditions in the regions where failure initiates or propagates. In other words, the engineering or macro-properties of the interface needed for analysis at the macro-level are very much influenced by the properties at the micro-scale.

Micro-scale deformations near the crack tip can be quantified based on the mechanical and optical interferometry methods in conjunction with the use of Scanning Electron Microscope (SEM) such as the electron beam Moire method (Dally and Read 1994, Lee and Read 1995, Drexler and Bergen 1999). However, the interferometry-based methods require the indirect evaluation of the displacement field by the determination of the order of the fringe pattern—a difficult task. Also, the presence of a dimple or lack of flatness in the vicinity of the crack tip may introduce a large error in the evaluation of displacements based on the fringes. Furthermore, these methods are inflicted with errors arising from rigid body motion.

In order to avoid these shortcomings, Theocaris et al. (1988) introduced a relative displacement method for direct evaluation of the displacement field around the crack tip by using a SEM. Theocaris (1990) improved this method by measuring the relative displacements of points along radial lines with respect to reference points deposited during the surface preparation process. Based on the concept of least square minimization, these relative displacement measurements were used to calculate the unknown coefficients of the series solution representing the elastic displacement field around the crack tip in a homogenous material, thus leading to the stress intensity factors. This approach is not influenced by the rigid-body movement, and does not require the exact position of the original crack tip location. Furthermore, it is not based on any fringe analysis.

Poursartip et al. (1998) recently reported a similar approach also using a Scanning Electron Microscope (SEM) to directly measure the Crack Opening Displacement (COD) and Crack Shear Displacement (CSD) in order to calculate the local energy release rate. They measured the relative crack surface displacements at landmark locations. Their study showed that the global energy release rate does not reflect the conditions at the crack tip. Therefore, the measurement of the energy release rate at the micro-level is of primary importance.

The relative normal and shear displacements of the crack faces can be extracted from images by measuring the change in distance between the specific points of crack profile before and after loading. After initiating a crack in the underfill between the silicon chip and the organic substrate, we have measured the relative crack surface displacements by monitoring the particular points behind the crack tip as shown in Figure 1. As the loading is increased, the relative crack surface displacements away from the crack tip is shown in Figure 2. As shown in this figure, the crack surface displacements, dU and dV, in the horizontal and vertical directions are dependent on the location of the measurement points immediately behind the crack tip. This raises the well-known concern of COD approach on the selection of the measurement location behind the crack tip.

There are no studies that investigate the process-dependent interface fracture parameters at the micro-level. As mentioned previously, combined mechanical and/or thermal loading is of extreme importance in electronic components requiring the critical interface fracture parameters.

Therefore, we have developed a technique, similar to the methods developed by Theocaris (1990), to determine the in-situ interface fracture parameters, and investigate the influence of thermal loading on these parameters by combining the micro measurements with the predictive analysis for the stress and strain fields around the interface crack tip.

Experimental Measurements

The specimens are prepared by sectioning the actual electronic components to be provided by Intel Corporation. After the sectioning and polishing processes, a notch is introduced at the junction of the chip and the substrate under an optical microscope. Then, the specimen is subjected to a three-point bending with a small load in the SEM to generate a sharp crack initiating from the notch. This procedure is controlled by monitoring the response of the load-displacement curve as shown in Figure 3.

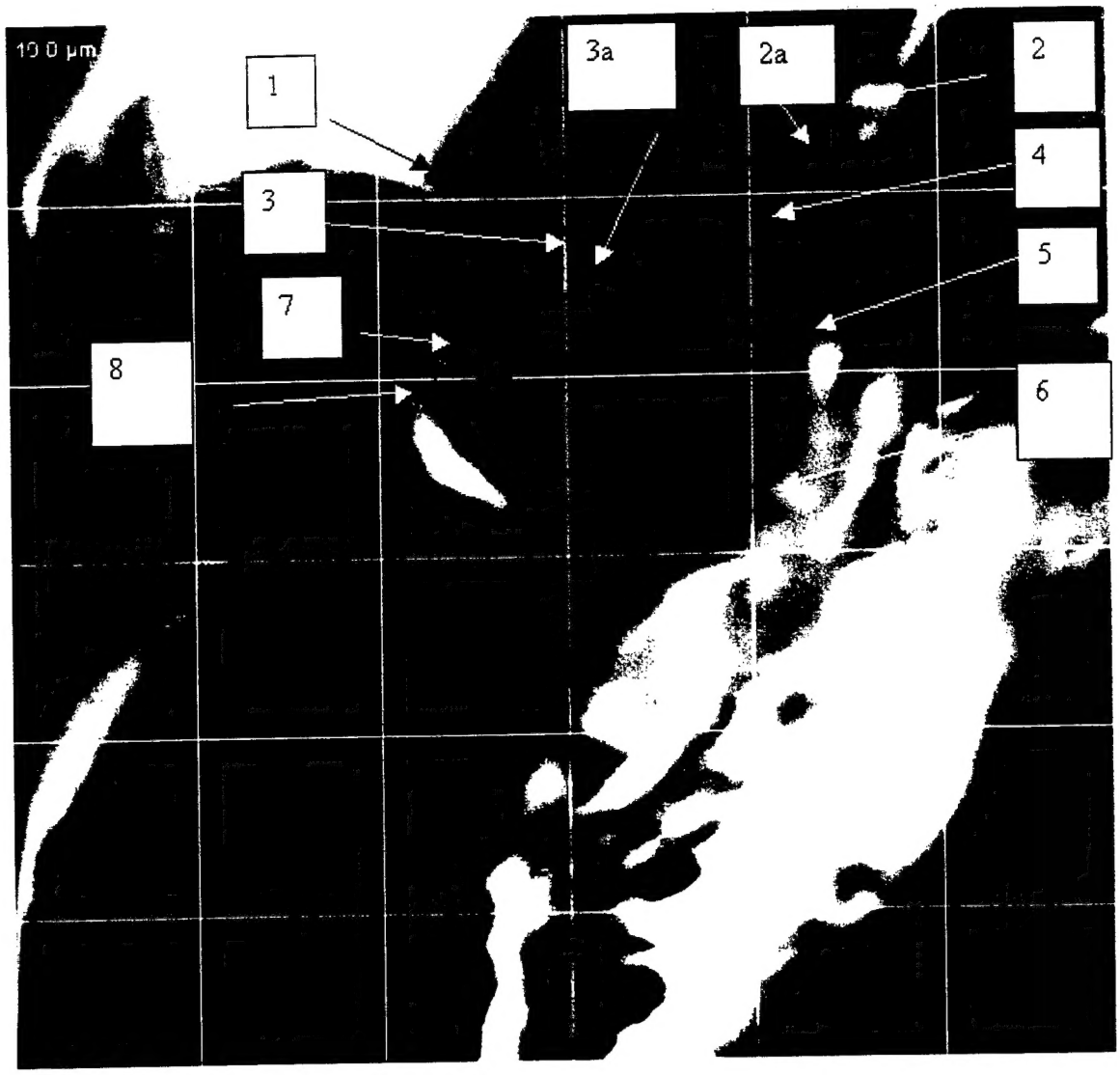


Figure 1. Reference points monitored behind the crack.

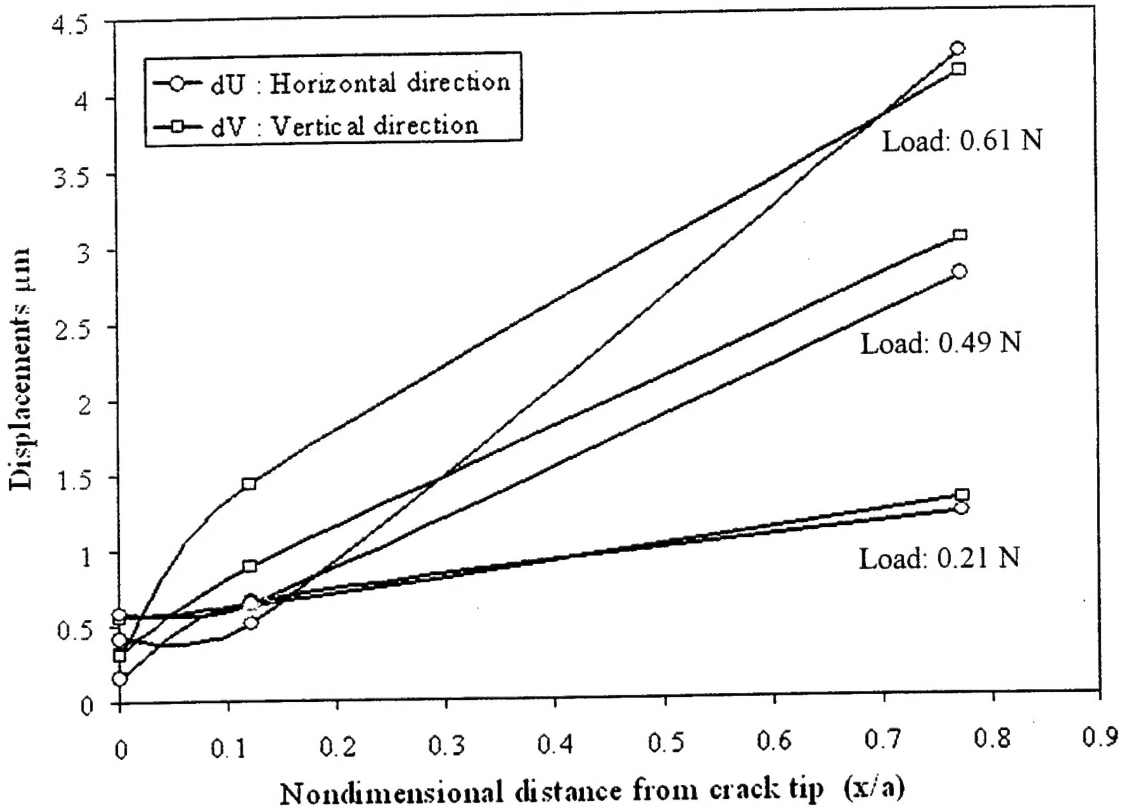


Figure 2. Relative crack surface displacements away from the crack tip as the applied load increases under three-point bending test.

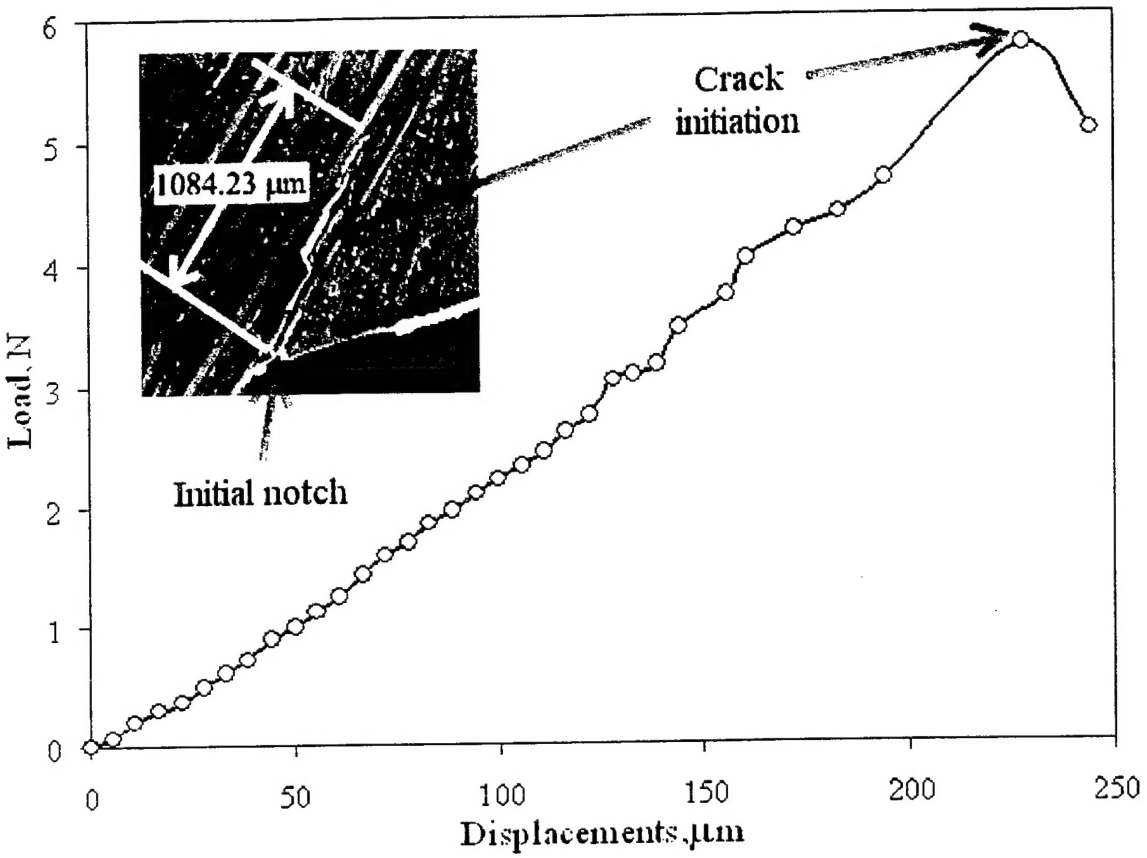
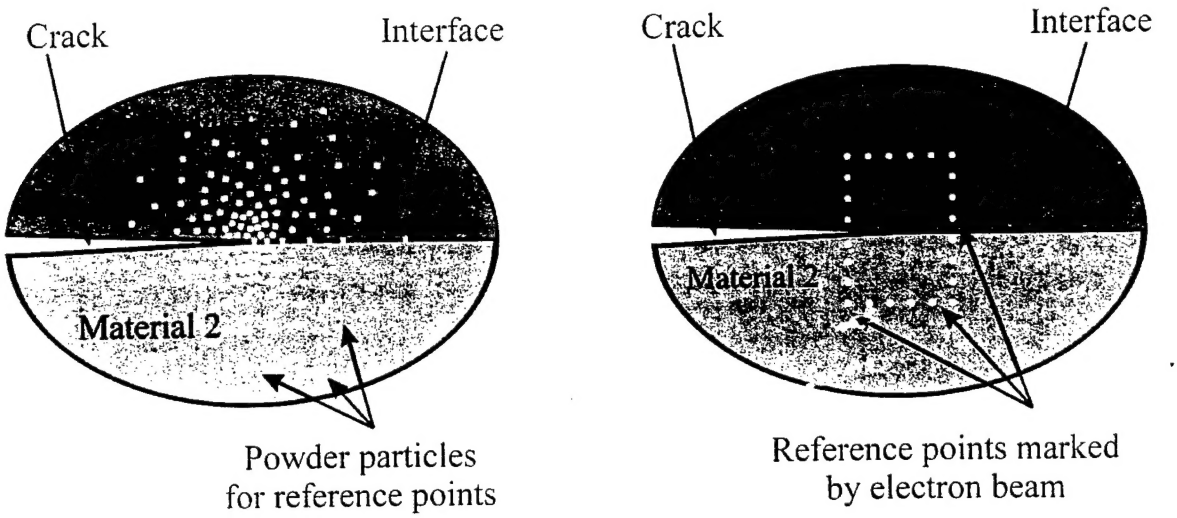


Figure 3. Crack initiation from a notch under a three point bending test.

After introducing the crack in the interface (adhesive), the surfaces of the specimen is coated with a thin layer of gold and sprayed with a very fine powder. The powder particles cemented on the coated surface provide the reference points suitable for the measurement of relative displacements. The reference points can also be located at desired locations by using the electron beam of the SEM. These reference points are labeled (identified) based on their coordinates. The schematic of these reference points with respect to the crack tip are shown in Figure 4.

The specimens are subjected to mechanical and thermal loading by using the sub-stage load cell in the SEM chamber. Via the imaging system for the scanning electron microscope, the displacement field around the crack tip is recorded as the specimen is subjected to loading. The displacement images are captured through the digital microanalysis system. This spectral analysis and digital imaging system with digital beam control enables the determination of the relative displacements by monitoring the reference points.



Powder particles for reference points

Reference points marked by electron beam

Figure 4. Methods of marking reference points around the crack tip.

However, this high-resolution method for measuring the relative displacements around the interface crack tip in specimens prepared from electronic components assembly poses the following milestones:

- Different sectioning techniques of the electronic components to minimize damage to specimens
- A more controlled method of introducing the initial crack
- Deposition of particles as reference points or introducing reference points by using the electron beam
- Thermal cycling of the specimen in the SEM chamber

Equipment Acquired

The following equipment and instrumentation have been acquired with this grant:

Cooling/heating tensile and bending substage for the SEM

A 100 lb tensile sub-stage, three-point bending fixture load cell and an extensometer, heating and cooling accessory (-130°C to 200°C), Oxford Instruments America, Inc.,

Electron Digital Scanning with Digital Imaging and Digital Beam Control

Kevex-SIGMA fully loaded KS2 Level 2 microanalysis system with Digital Imaging and spectral processing model, IXRF System, Inc.

MTS fatigue testing machine control system

TestStar IIs Controller and 506.02 HPU, MTS Systems Corporation.

Conclusions and Remarks

This project led to a new approach to determine the in-situ critical interface fracture parameters. This technique combines the experimental measurements at the micro-scale and analytical calculations at the macro-scale. Measurement technique is developed for micro-displacements near the interface crack tip by employing an SEM and an imaging system. The specimens are subjected to mechanical and/or thermal loading in the cooling/heating bending sub-stage of the Scanning Electron Microscope (SEM).

This method will also quantify the divergence of material properties from their bulk values as dimensions are reduced and interfaces are approached. Furthermore, the measurement of strain and observation of deformation at high magnification and observation of failure modes will help in verification of mathematical models and simulations of micro-scale mechanical behavior. For example, we have observed the coalescence of damage zone ahead of a crack as shown in Figure 5. Through image processing as shown in Figure 6, the growth of the damage zone can be determined as the load is increased prior to coalescence as shown in Figure 7, leading to its critical value.

This technique will advance the understanding of fundamental issues associated with dissimilar material joints, and provide information regarding interface material properties. The results of this project will improve the usefulness of modeling and simulation in the design and manufacture of the electronic components and interconnect structures.

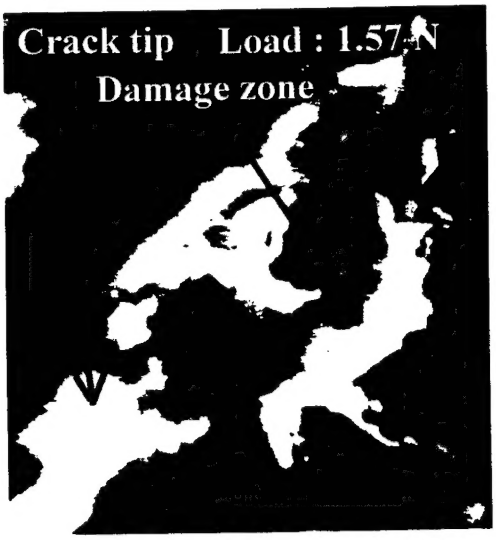


Figure 5. Damage zone growth ahead of the crack tip.

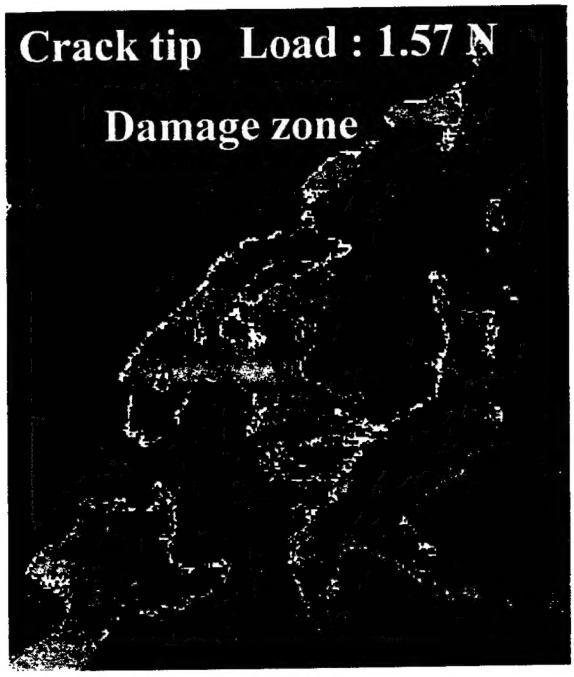


Figure 6. Image processing of the damage zone.

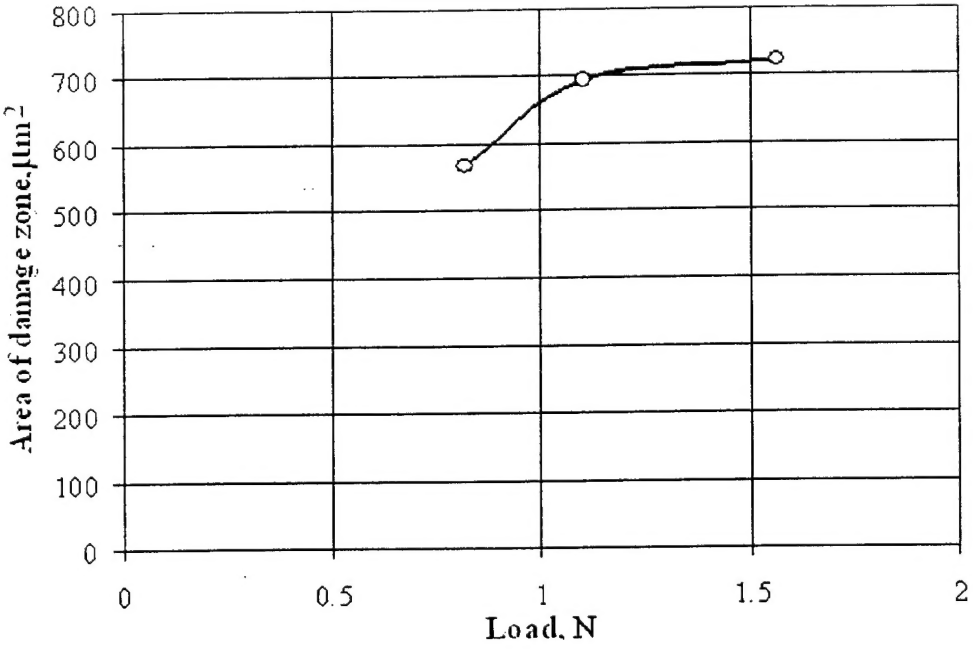


Figure 7. Damage zone growth near the crack tip.